

The Canada France Redshift Survey VIII: Evolution of the Clustering of Galaxies from $z \sim 1$.

O. Le Fèvre¹

*DAEC, Observatoire de Paris-Meudon, 92195 Meudon, France
lefevre@daec.obspm.fr*

D. Hudon, S.J. Lilly¹

Department of Astronomy, University of Toronto, Toronto, Canada M5S 1A7

David Crampton¹

Dominion Astrophysical Observatory, National Research Council of Canada, Victoria, Canada

F. Hammer¹ and L. Tresse¹

DAEC, Observatoire de Paris-Meudon, 92195 Meudon, France

ABSTRACT

This paper analyzes the spatial clustering of galaxies in the Canada-France Redshift Survey (CFRS).

We have used the projected two-point correlation function, $w(r_p)$, to investigate the spatial distribution of the 591 galaxies with secure redshifts between $0 \leq z \leq 1.3$ in the five CFRS fields. The slope of the two-point correlation function for the sample as a whole is $\gamma = 1.64 \pm 0.05$, very similar to the local slope, and γ is therefore not strongly evolving with redshift. However, the amplitude of the correlation function decreases strongly with increasing redshift, so that at $z \approx 0.6$ it is a factor of 10 lower (for $q_0 = 0.5$) than for a similarly-selected local galaxy population, on scales $0.1 < r < 2h^{-1}$ Mpc ($q_0 = 0.5$). As a whole, the CFRS data is adequately represented by $r_0(z = 0.53) = 1.33 \pm 0.09h^{-1}$ Mpc for $q_0 = 0.5$, and $r_0(z = 0.53) = 1.57 \pm 0.09h^{-1}$ Mpc for $q_0 = 0$.

Unless the galaxy population at high redshift is quite different from any population seen locally, an unlikely possibility, then this implies growth of clustering as described by the evolutionary parameter ϵ to be between $0 < \epsilon < +2$.

¹Visiting Astronomer, Canada-France-Hawaii Telescope, which is operated by the National Research Council of Canada, the Centre de Recherche Scientifique of France and the University of Hawaii

No difference in the clustering of red and blue galaxies is seen at $z \geq 0.5$, although at lower redshifts, $0.2 \leq z \leq 0.5$, blue galaxies are somewhat less strongly correlated than the redder galaxies, as seen in local samples. This effect could be the equivalent for field galaxies to the Butcher-Oemler effect seen in clusters of galaxies. The cross-correlation functions between red and blue samples have comparable amplitudes to the auto-correlation functions of each.

The distribution and power spectrum of pair separations does not indicate significant periodic patterns in the distribution of galaxies along the lines of sight. Finally, the densest structures in the survey are identified and characterized, including the structure at $z = 0.985$ in the 1415+52 field, reported previously, and a new cluster of galaxies at $z = 0.78$ in the 1000+25 field.

Subject headings: galaxies: clustering – cosmology: large scale structure of the universe
– galaxies: distances and redshifts – galaxies: evolution – cosmology: observations

1. INTRODUCTION

Deep redshift surveys can provide key information on the evolution of the spatial distribution of galaxies with cosmic time. In a deep “pencil-beam” survey, the line of sight is expected to cross many structures similar to the sheets, walls and voids identified in the nearby universe, with rarer encounters of denser regions associated with clusters of galaxies. Such surveys can provide information on the existence and properties of large scale structure in the Universe at high redshift.

It is expected that the clustering of galaxies may well change with epoch in an expanding universe in which structures evolve and grow under the action of gravity. As a consequence, the two-point correlation function $\xi(r)$ should change with cosmic epoch, but the exact form of this evolution is at present poorly known.

There have been many studies of the local $\xi(r)$ in surveys such as the CfA, Stromlo-APM, SSRS, IRAS and others (see e.g. Davis & Peebles 1983; Loveday et al. 1995, Fisher et al. 1994; Benoist et al. 1995). They indicate a power-law behaviour with $\xi(r) = (r/r_0)^{-\gamma}$. Values for the correlation length r_0 range from 3.8 to $7.5 h^{-1}$ Mpc with a possible dependence on luminosity and galaxy type (Loveday et al. 1995) and $\gamma \sim 1.7$. At higher redshifts, two approaches can be followed to measure $\xi(r)$. The first is to invert the projected angular two-point correlation function $w(\theta)$ through the Limber equation using an observed or predicted redshift distribution $N(z)$ appropriate to the observed limiting magnitude of the galaxy sample. From the angular correlation function $w(\theta)$, Efsthathiou et al. (1991) have shown that faint galaxies, which are associated with the “excess” in the blue number counts, are rather weakly clustered. At shallower depths, where spectroscopic surveys are possible, Hudon and Lilly (1995) inverted a measurement of $w(\theta)$ using the redshift distribution based on the CFRS and find a correlation length

of $r_0 = 1.9 \pm 0.1 h^{-1}$ Mpc at $z \sim 0.5$.

The alternative approach is to directly compute $\xi(r)$ from the distance information for individual galaxies that is present in deep redshift surveys. A direct computation of $\xi(r)$ from the redshift surveys of Broadhurst et al. (1988) and Colless et al. (1990, 1993) was carried out by Cole et al. (1994), who did not find any evidence for evolution in the comoving correlation length for $z < 0.25$. The deep I-band selected CFRS sample (see Lilly et al. 1995a, CFRS-I; Le Fèvre et al. 1995, CFRS-II; Lilly et al. 1995b, CFRS-III; Hammer et al. 1995, CFRS-IV; Crampton et al. 1995, CFRS-V) provides for the first time the opportunity to directly evaluate the evolution of the two-point correlation function $\xi(r)$ over the redshift range $0 < z < 1$.

Interpretation of apparent changes seen in $\xi(r)$ with epoch must be approached with caution. Redshift surveys trace large scale structures by their galaxies. Since different types of galaxies exhibit different clustering properties at the present epoch, apparent changes in the clustering of galaxies at different epochs may well reflect a combination of either or both of the “true” evolution of large scale structure and/or changes in the population of galaxies being observed. The latter can arise either through evolution of the galaxy population or through the way the galaxies are being selected at different redshifts. Unfortunately, the evolution of the mix of different galaxy populations is poorly understood at the present time. Thus, any changes observed in the clustering strength represent the “apparent” evolution in the clustering, and the true growth of structure can only be determined by making assumptions as to the nature of the galaxy population dominating the samples at high redshifts. A further frustrating ambiguity arises from making different assumptions about the value of the deceleration parameter q_0 . Assuming a lower value of q_0 generally increases the strength of clustering implied from a given set of observations at high redshift. This reduces the growth that is

implied in clustering up to the present epoch, an observational reduction that is to a certain degree matched by the theoretical expectations of reduced growth in low density Universes.

In addition to the small-scale clustering that can be measured with $\xi(r)$, there has been considerable interest in the large scale structure information provided by deep “pencil-beam” surveys since Broadhurst et al. (1990) reported that the distribution of redshifts in a combination of survey at the North and South poles up to $z \sim 0.5$ is occurring at a preferred scale of $\sim 128 h^{-1}$ Mpc.

In this paper we first compute $\xi(r)$ from the CFRS sample by means of the projected spatial two-point correlation function $w(r_p)$ as a function of redshift. We examine the correlation function for sub-samples of galaxies split by intrinsic color, and the cross-correlation function between these. We then compute and discuss the auto-correlation function of the galaxy distribution to examine the galaxy pair distribution vs. comoving distance, and the power spectrum of the redshift distributions. We finally quantify and examine the most prominent over-densities seen in the survey.

Except where noted to the contrary, values of $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$ are used throughout the paper.

2. THE CFRS SAMPLE

The CFRS has been described in detail elsewhere (CFRS I-V). The statistically complete subsample consists of 943 objects selected in five $10' \times 10'$ fields to have $17.5 \leq I_{AB} \leq 22.5$, without regard to color or morphology, and with minimal surface brightness selection. The sample is 85% spectroscopically identified and this paper is based on the 591 galaxies in the CFRS that have secure redshifts. The redshifts extend up to $z \sim 1.3$, with a median redshift $\langle z \rangle = 0.56$. More than 350 galaxies have $z \geq 0.5$.

The I-band selection criterion corresponds to selection in the rest-frame $4200 \leq \lambda \leq 5500 \text{ \AA}$ re-

gion for redshifts $0.5 \leq z \leq 1$, and thus the sample of high redshift galaxies is, in principle, well-matched to most local samples of galaxies. The field dimension of $10'$ corresponds to a comoving dimension of $3.3 h^{-1} \text{ Mpc}$ at $z \sim 0.5$ and to $5.3 h^{-1} \text{ Mpc}$ at $z \sim 1$, dimensions comparable to the $z = 0$ correlation length.

The CFRS sample thus provides an unprecedented opportunity both to investigate the clustering properties of galaxies at different epochs, and for different intrinsic colors, from a time when the universe was $\sim 40\%$ of its present age, and to identify over-densities out to redshifts ~ 1 (one such structure was reported in Le Fèvre et al. 1994).

One significant complication with using the CFRS to study the clustering of galaxies is the highly non-uniform spatial distribution of the objects selected for spectroscopic study within each field (see CFRS II). The objects are located primarily in three parallel strips for each of the 5 fields, within which almost 100% spectroscopic sampling was obtained, separated by regions where very few spectroscopic observations were carried out. Our technique for dealing with this uneven spatial sampling is discussed in §3.3.

The redshift accuracy is 0.0019 r.m.s, or a velocity accuracy of 550 km s^{-1} . To account for this effect in evaluating the evolution of $\xi(r)$ we have used the projected two point correlation function $w(r_p)$ as described in Section 3.2.

3. THE COSMIC EVOLUTION OF THE TWO-POINT CORRELATION FUNCTION

3.1. The epoch-dependent 2-point correlation function $\xi(r, z)$

The local two-point correlation function is well represented by a power-law (Davis and Peebles 1983)

$$\xi(r) = \left(\frac{r}{r_0}\right)^\gamma$$

and the epoch-dependent correlation function is usually expressed in terms of an evolutionary parameter ϵ (Groth and Peebles 1977; Efstathiou et al. 1991),

$$\xi(r, z) = \xi(r, 0) \times (1 + z)^{-(3+\epsilon)}$$

Thus, the correlation length can be written

$$r_0(z) = r_0(0) \times (1 + z)^{-(3+\epsilon)/\gamma}$$

To avoid confusion, it should be noted that the correlation length $r_0(z)$ is here the correlation length (in physical units) that would be measured by a local observer at the epoch in question. Thus the correlation length will evolve (as $(1 + z)^{-1}$) even if the clustering pattern is fixed in comoving space.

In the case of a clustering pattern fixed in comoving coordinates, clustering does not grow with time, and $\epsilon = \gamma - 3 = -1.3$ for $\gamma = 1.7$. When bound gravitational units keep a fixed physical size, the clustering growth is the result of the increasingly diluted galaxy background (it is effectively the voids that are “growing”), and $\epsilon=0$ (Efstathiou 1991; Carlberg 1991). For a standard CDM scenario, the mass clustering should grow in the linear regime with $\epsilon \sim 0.7$ on $\sim 1 \text{ h}^{-1} \text{ Mpc}$ scales, (Davis et al., 1985). However, clustering growth of galaxies in CDM may not follow the linear theory (Brainerd & Villumsen 1994).

3.2. Projected 2-point correlation function $w(r_p)$

To avoid the effect of peculiar velocities and redshift measurement errors in evaluating the spatial correlation function $\xi(r)$, we have used the projected function $w(r_p)$ (Davis & Peebles 1983), generalized to the observation of galaxies at high redshifts:

$$w(r_p) = \frac{c}{H_0 \times (1 + z)^2 \times (1 + 2q_0z)^{1/2}} \int_{-\delta z}^{+\delta z} \xi(r_p, \pi) dz \quad (1)$$

with

$$r_p = (d_\theta(i) + d_\theta(j)) \times \tan(\theta_{ij}/2)$$

where d_θ is the angular diameter distance:

$$d_\theta = \frac{c}{H_0} \times \frac{q_0z + (q_0 - 1)(-1 + (1 + 2q_0z)^{0.5})}{q_0^2(1 + z)^2}$$

θ_{ij} is the apparent angular separation between galaxy i and galaxy j (degrees). Here π is the radial distance between the galaxies in physical units. The quantity

$$\frac{c}{H_0 \times (1 + z)^2 \times (1 + 2q_0z)^{1/2}} dz \quad (2)$$

is the increment in physical distance. In equation (1), we take the $(1 + z)^2(1 + 2q_0z)^{0.5}$ term out of the integral because the effects of both peculiar motions and redshift errors are constant in velocity space rather than in physical distance space. Taking this redshift-dependant term out means that equation (1) is valid only when the correlation function is constructed from a sample of galaxies occupying only a small range of redshifts so that the term outside of the integral is roughly constant. With $\xi(r) = (r_0/r)^\gamma$ and $r_p \ll cz/H_0$, $w(r_p)$ becomes (Davis and Peebles 1983)

$$w(r_p) = \frac{\Gamma(1/2)\Gamma[(\gamma - 1)/2]}{\Gamma(\gamma/2)} \times r_0^\gamma \times r_p^{1-\gamma} \quad (3)$$

($\frac{\Gamma(1/2)\Gamma[(\gamma-1)/2]}{\Gamma(\gamma/2)} = 4.0, 4.3$ for $\gamma = 1.71$ and 1.64 respectively) so that computing $w(r_p)$ provides a measurement of r_0 and γ .

We have computed $\xi(r_p, \pi)$ with the standard estimator

$$1 + \xi(r_p, \pi) = \frac{DD(r_p, \pi)}{DR(r_p, \pi)}$$

where DD is the number of data-data pairs and DR the number of data-random pairs (10000 random trials were performed). The projection to $w(r_p)$ was then done following equation (1) with $\delta z = 0.0075$. Three independently written codes (by DH, OLF, SJL) have been used for this computation as described below.

3.3. Treatment of non-uniform spatial sampling in the CFRS

In essence, the correlation function is based on a comparison between the observed distribution of galaxies and that expected from a random distribution of points in space, and most estimators of the correlation function are based on the Monte Carlo generation of large numbers of “random” data sets. Unless spatial completeness is achieved, which is extremely costly in telescope time at the depth of the CFRS, the use of multi-object spectrographs to generate deep redshift surveys usually imposes a spatial selection function on the final galaxy catalogue relative to the distribution of galaxies on the sky. This selection function arises due to the various constraints on the positioning of the spectroscopic apertures (whether slits or fibres) on the sky. An obvious example is a possible bias in a single mask against near neighbours, due to the finite slit length. Other more subtle effects are conceivable, including a possible radial dependence within the field in the success rate in securing spectroscopic identifications, etc. In any event, the spatial selection function must be properly accounted for in the generation of the “random” data sets.

The observing process of the CFRS restricted the selection of objects to three parallel strips per field (CFRS-II). This geometry was imposed by the mask design which maximised the multiplexing gain in the spectroscopy by allowing three non-overlapping spectra in the direction parallel to the dispersion. When fields were re-observed, emphasis was placed on filling in objects missed in these strips and on broadening the strips rather than on observing objects in the areas between the strips. This resulted in strips with typical width $\sim 1'$ and length $\sim 10'$. This strategy ensured almost 100% spatial sampling (with virtually no bias against close pairs of galaxies, CFRS-II) within each strip, but left large areas with very low ($\sim 0\%$) spatial sampling. Thus, in the final catalogue, while there

should be almost no bias against near neighbours, the distribution of galaxies on arcmin scales is highly non-uniform.

This non-uniform spatial distribution of those galaxies identified spectroscopically considerably complicates the generation of the “random” data sets used in the computation of the correlation function. One possible solution would have been to generate the random data sets from rectangular areas matching these strips. However, in our sample, the details of the widths and sampling completeness within these strips varied from field to field due to the differing numbers of masks observed in each field (see the figures in CFRS-II-IV). In order to guarantee that the random data sets had *exactly* the same spatial selection function as the CFRS galaxy sample, each of the random data sets was drawn from *exactly the same* (α, δ) positions as the overall galaxy sample – i.e. the 591 galaxies with secure redshifts (i.e. Confidence Class ≥ 2) in the statistically complete CFRS sample (see CFRS-V). In each random data set, these positions were assigned different, random, redshifts. We adopted three different methods for assigning the random redshifts and implemented these in three independent codes for computing $w(r_p)$. These three methods were (a) to use redshifts randomly drawn from the smoothed $N(z)$ for the whole sample generated from the luminosity function analysis (see Figure 9 of CFRS VI); (b) to use redshifts randomly generated from the observed $N(z)$, summed over all fields, and binned in intervals of 0.05 in z to smooth out the picket-fence distribution; and (c) to use the observed redshifts from the sample with the addition of a random component in redshift of $\Delta z \leq 0.2$. The results from these three methods agree to within the nominal uncertainties obtained from Poisson statistics. In addition, trials show that adding random offsets in the range 0 to 10 arcsec to the (α, δ) centers for the random data sets has no significant effect on the derived $w(r_p)$.

The effect of using the (α, δ) positions of the

objects identified spectroscopically for the “random” samples is simply to bias the estimation of the background density of galaxies. The “background” density of galaxies at angular separation θ is set by the data itself, and since galaxies are clustered with non-zero $w(\theta)$, this background density will be biased high, leading to an underestimate of $w(r_p)$. The effect of this “random sampling bias” is similar to the well known integral constraint encountered in constructing the projected 2-dimensional $w(\theta)$ from finite data sets.

The bias in the background density is simply given by the observed amplitude of the projected 2-D correlation function on the angular scale corresponding to the value of r_p at the redshift in question. Thus since

$$1 + w = \frac{n_{\text{observed}}}{n_{\text{random}}}$$

it follows that

$$1 + w_{\text{obs}}(r_p) = \frac{1 + w_{\text{real}}(r_p)}{1 + w(\theta)}$$

or

$$w_{\text{real}}(r_p) = w_{\text{obs}}(r_p) \times (1 + w(\theta)) + w(\theta)$$

For $w(r_p) \gg 1 \gg w(\theta)$, as we have, this bias is a small angle-dependent multiplicative factor.

In the current analysis, the scale of most interest is $0.1h^{-1} < r < 2h^{-1}\text{Mpc}$, corresponding to $27'' < \theta < 4'5$ at $z \sim 0.56$, the median redshift of the survey. Most of the signal is on the larger scales. The projected $w(\theta)$ on these scales and at these depths is known from large samples of red-selected galaxies (see e.g., Infante and Pritchett 1995; Hudon and Lilly 1995). At $19.0 < R < 23.5$, which is broadly equivalent to our $17.5 \leq I_{AB} \leq 22.5$ sample, Hudon and Lilly (1995) find that $w(\theta)$ varies between $0.01 < w(\theta) < 0.07$ on scales 3.3 arcmin down to $27''$. Since our $w(r_p)$ is greater than 10 (on all scales at all redshifts) this bias has a small effect, especially at the larger scales around $1 h^{-1}$

Mpc where our S/N is greatest. The bias will decrease the apparent slope, γ , by approximately 0.03. This bias is sufficiently small that we have chosen to ignore it and have not attempted to correct for it.

3.4. Results

In Figure 1 we show the projected correlation function $w(r_p)$, computed in the interval $25h^{-1}\text{kpc} \leq r_p \leq 2h^{-1}\text{Mpc}$ for the $0 \leq z \leq 1$ CFRS survey. This has a slope $\gamma = 1.64 \pm 0.05$. This indicates that, while γ is marginally lower than observed in local samples (e.g. $\gamma = 1.71$ for the Stromlo-APM redshift survey, Loveday et al., 1995), it is not changing significantly at the mean depth of the CFRS. In fact, the small difference can be partly accounted for by the effect of the random sampling bias discussed in §3.3. A similar result has been obtained from $w(\theta)$ reaching similar depth (Hudon & Lilly 1995).

In order to examine evolution in the amplitude of the correlation function, the sample was split into three redshift bins $0.2 \leq z \leq 0.5$, $0.5 \leq z \leq 0.75$, $0.75 \leq z \leq 1$ (the redshift bins match those of our analysis of the evolving luminosity function - see CFRS VI). The resulting $w(r_p)$ are shown in Figure 2. These have been characterized by fitting power-laws with both r_0 and γ free parameters and, for uniformity, by fitting a power-law with fixed $\gamma=1.64$, following equation (2). In the latter case, $r_0(z=0.34) = 1.83 \pm 0.18$, $r_0(z=0.62) = 1.10 \pm 0.15$ and $r_0(z=0.86) = 1.05 \pm 0.10$ are found. Errors on $w(r_p)$ over the redshift range $0 \leq z \leq 1$ have been derived from the estimates of the correlation function obtained in each of the five independent fields of the CFRS, which indicate values larger than expected from Poisson behavior, compatible with expectations from simulations (Landy & Szalay 1993). For the computation of $w(r_p)$ in the three redshift bins and in color-redshift bins, error bars on $w(r_p)$ have been increased by 50% from the Poisson value, as the number of galaxies in each redshift/color bin is not sufficient to compute $w(r_p)$ for each indi-

vidual field. Error bars indicated in Figure 1 are from the field-to-field variations and are $\approx 50\%$ higher than the Poisson values. In addition, it should be noted that the three independent codes found essentially identical results, indicating that computational errors are negligible.

The above analysis was repeated for $q_0=0$. From equation (1), the implied r_0 is expected to be higher in a lower density universe, both because of the $(1 + 2q_0z)^{0.5}$ factor and because the change in angular diameter distance means a given angular scale corresponds to a larger physical scale. Indeed, we find $r_0(z=0.34) = 2.1 \pm 0.15$, $r_0(z=0.62) = 1.36 \pm 0.13$ and $r_0(z=0.86) = 1.45 \pm 0.10$ for the three redshift bins $0.2 \leq z \leq 0.5$, $0.5 \leq z \leq 0.75$, $0.75 \leq z \leq 1$ respectively.

The sample has also been divided by the intrinsic color of the galaxies, by dividing the sample into galaxies redder and bluer than the Coleman, Wu and Weedman (1980) Sbc spectral energy distribution. It was shown in CFRS-VI that the evolution of the luminosity function of galaxies is quite different for these two color bins. In Figure 3, we show $w(r_p)$ for the blue and red sub-samples in the redshift ranges $0.2 \leq z \leq 0.5$ and $0.5 \leq z \leq 0.8$. Fitting again with a $\gamma = 1.64$ power-law, we find $r_0(z=0.34) = 2.10 \pm 0.2$ and $r_0(z=0.34) = 1.45 \pm 0.25$, and $r_0(z=0.65) = 1.21 \pm 0.15$ and $r_0(z=0.65) = 1.31 \pm 0.15$ for the red and blue samples respectively. Finally, within these same redshift bins, the cross-correlation functions between red and blue subsamples has also been computed. We find $r_0(z=0.34, \text{red-blue}) = 1.93 \pm 0.39$, $r_0(z=0.34, \text{blue-red}) = 1.85 \pm 0.41$, $r_0(z=0.65, \text{red-blue}) = 0.95 \pm 0.10$ and $r_0(z=0.65, \text{blue-red}) = 1.10 \pm 0.05$.

Results on the various $w(r_p)$ fits are summarized in Table I.

4. DISCUSSION

4.1. The evolution of $\xi(r, z)$

Our data indicates that the correlation length is decreasing with redshift, with the amplitude

of the correlation function $\xi(r)$ being lower by a factor ~ 3 at $z \sim 0.6$ compared to $z \sim 0.3$. However, the errors on our $r_0(z)$ points are such that strong constraints can not be placed on ϵ , the apparent rate of the clustering evolution, from our data taken by itself. A formal fit to the 3 CFRS data points shown plotted in Figure 4 yields $\epsilon = 0.4 \pm 1.1$, $r_0(0) = 3.3 \pm 1.0$. Furthermore, as a result of the apparent magnitude selection $17.5 \leq I_{AB} \leq 22.5$, the CFRS data samples different parts of the galaxy luminosity function at different epochs (see, e.g., Figure 5 of CFRS VI). In the redshift bins $0.2-0.5$, $0.5-0.75$, $0.75-1$, the correlation function applies to galaxies with $-17.0 \leq M(B_{AB}) \leq -20.0$, $-18.0 \leq M(B_{AB}) \leq -21.0$, $-19.0 \leq M(B_{AB}) \leq -21.0$ respectively (for $h = 1$). If sub- L^* galaxies are less strongly correlated than L^* and super- L^* galaxies, as reported from local samples (Loveday et al. 1995; Benoist et al. 1995), and if this still holds at higher redshifts, then, for consistency, our r_0 measurement for the $0.2 < z < 0.5$ bin should be revised upwards, by perhaps as much as 50% (based on the trends in Loveday et al. 1995), leading to a steeper apparent decline with redshift and a change to a larger value of the apparent value of ϵ .

In order to determine the best value of $r_0(z)$ representing the whole CFRS sample, we examined all the combinations $(r_0(0), \epsilon)$ giving an acceptable fit to the high redshift points. All these “best fit” $r_0(0)$ vs. ϵ curves intersect at $z \sim 0.53$ with $r_0(z = 0.53) = 1.33 \pm 0.09h^{-1}$ Mpc for $q_0 = 0.5$ and $r_0(z = 0.53) = 1.57 \pm 0.09h^{-1}$ Mpc for $q_0 = 0$.

Stronger constraints than formally allowed by the three high redshift $r_0(z)$ points on the apparent value of ϵ can be derived when our r_0 measurements at high redshift are taken together with local measurements. For a given value of $r_0(0)$, our data allow to set ϵ to ± 0.35 . We can thus see what combinations of “galaxy population”, parameterized by $r_0(0)$, and “structure evolution”, parameterized by ϵ , are permitted by

the CFRS data. Davis and Peebles (1983) derived $r_0 = 5.4h^{-1}$ Mpc from the CfA survey limited to $m_B < 14.5$, and according to Fisher et al. (1994), the IRAS sample has $r_0 = 3.8h^{-1}$ Mpc. The correlation length has been suspected to be dependent on the luminosity and the type of the galaxies, with less luminous galaxies being less strongly clustered than the more luminous galaxies, and early type galaxies more strongly clustered than late type ones with a range of correlation length between $2.9 \leq r_0 \leq 7.4h^{-1}$ Mpc in the Stromlo-APM redshift survey (Loveday et al. 1995) and $3.9 \leq r_0 \leq 14.5h^{-1}$ Mpc for the SSRS2 (Benoist et al., 1995). The various values of r_0 reported by Loveday et al. (1995) are shown plotted at $z \approx 0$ in Figure 4, together with lines representing different values of ϵ .

We discuss here three specific possibilities:

(1) If there was no growth in clustering, i.e., the clustering pattern is fixed in comoving coordinates, $\epsilon = -1.3$, then our observed clustering at high redshift would imply a local value of $r_0(0) = 2.0 \pm 0.2h^{-1}$ Mpc for $q_0 = 0.5$, $r_0(0) = 2.5 \pm 0.2h^{-1}$ Mpc for $q_0 = 0$, a clustering strength much lower than for any local population of galaxies yet observed. Given the modest changes in the galaxy luminosity function constructed from this same CFRS sample (CFRS VI and discussion below), the existence of such a currently-unknown galaxy population is extremely unlikely. We therefore conclude that some growth of clustering *must* have occurred over this redshift range.

(2) If the physical size of clusters of galaxies had remained fixed with redshift, i.e., the $\epsilon = 0$ case, then $r_0(0) = 3.0 \pm 0.2h^{-1}$ Mpc is implied for $q_0 = 0.5$ ($r_0(0) = 3.9 \pm 0.2h^{-1}$ Mpc for $q_0 = 0.0$). The galaxies we observe at high redshift in the CFRS would have had to evolve with time into the most weakly clustered (low luminosity) galaxies in, for example, the Stromlo-APM survey (Loveday et al. 1995) or the SSRS (Benoist et al. 1995).

(3) Finally, for the CFRS galaxies to be representative of the local B-band selected samples

with roughly L^* luminosities would require rapid growth of the clustering, with $\epsilon \geq 1$. For instance, for the CFRS galaxies to evolve into local samples that have $r_0 = 5 \pm 0.15h^{-1}$ Mpc (Loveday et al. 1995), would require $\epsilon = 2.1 \pm 0.3$ for $q_0 = 0.5$.

Given this ambiguity in the interpretation, what is known about the galaxies that dominate the CFRS sample at $0.5 < z < 1.0$? The luminosity function of red galaxies in the CFRS shows little change over the redshift range of the survey, while the luminosity function of blue galaxies indicates either brightening of the luminosities by ~ 1.2 mag by $z \sim 0.75$, or a number density evolution of a factor 3 (CFRS VI). The morphologies of the galaxies are now being revealed by deep HST images (Schade et al. 1995; CFRS-IX). The majority of galaxies appear normal, representing the same range of Hubble types as seen locally. However, of the galaxies bluer than Sbc, 30% show asymmetric structure dominated by bright blue regions of star-formation and half have disks that are ~ 1 mag brighter than normal galaxies at $z = 0$. Thus the population at $z \sim 0.6$ is expected to be broadly similar to that seen in local B-selected samples of luminous galaxies, but with the likelihood of some luminosity evolution in at least part of the population. This suggests that scenarii similar to those discussed in (2) and (3) above are plausible, probably nearer the latter, and thus we believe that the “true” value of ϵ is likely to be between 0 and +2.

We emphasize that the results presented here are made possible by the large number of redshifts, and long baseline in cosmic epoch of the CFRS. Stronger constraints on the evolution of $\xi(r)$ from a direct measurement will require either much larger samples in the same redshift range, or the direct measurement of $\xi(r)$ at redshifts significantly in excess of one. An important gap in the Figure 4 could be filled in by analysis of a large sample of luminous galaxies at $z \sim 0.3$.

4.2. The effect of $q_0 \sim 0$

The effect of altering the assumed q_0 is straightforward to see in equation (1). The $w(r_p)$ changes due to both the different incremental comoving distance with redshift and the different angular diameter distance. Relative to the measurement inferred for $q_0 = 0.5$, the effect of decreasing q_0 is to increase the implied $r_0(z)$ by a factor

$$\frac{d_\theta(q_0)}{d_\theta(q_0 = 0.5)} \times \left[\frac{(1+z)}{(1+2q_0z)} \right]^{1/2\gamma}$$

For a high redshift sample at $z \sim 0.6$, going from $q_0 = 0.5$ to $q_0 = 0$ has the effect, for fixed $r_0(0)$, of reducing the implied value of ϵ by ~ 1 .

4.3. The clustering of blue and red subsamples

Given the known difference between the clustering of blue and red galaxies in the local Universe (see e.g. Loveday et al. 1995), the lack of a significant difference in the auto-correlation functions for blue and red subsamples at $z \geq 0.5$ is interesting. The blue-red and red-blue cross-correlation functions have comparable amplitudes to the auto-correlation functions, suggesting that the blue and red galaxies are well mixed at $z \sim 0.5$. If, as observed in local samples, early-type galaxies are more strongly correlated than late-type galaxies (e.g. Loveday et al., 1995), then the fact that we don't see a difference in clustering strength between red and blue samples for $z \geq 0.5$ is a strong evolutionary effect. The break-down of the clustering difference between blue and red galaxies in our CFRS sample is reminiscent of the Butcher-Oemler effect in clusters (Butcher and Oemler 1984), in which the fraction of blue galaxies in clusters, small at low redshift, increases with redshift to approach that in the field at $z \sim 0.5$, implying an elimination of the segregation of blue and red galaxies.

Although we have only a small number of galaxies at lower redshifts, and they are of generally lower luminosities, the difference we see in

the clustering strengths of blue and red galaxies in our own sample at $0.2 < z < 0.5$ (see Table 1), is consistent with the picture described above.

The similar auto-correlation and cross-correlation functions of the blue and red galaxies at $z > 0.5$ argues against a substantial admixture of any “new” population with radically different clustering properties at this depth, consistent with the indications from the luminosity function and the morphologies of the galaxies discussed above.

5. PAIR SEPARATIONS, POWER SPECTRUM

The distribution of pair separations (in comoving coordinates) in the CFRS has been computed for each individual field, as well as after summing the individual distributions. The distribution, shown in Figure 5, is quite smooth, with no obvious preferred separation in the combined data or in the individual fields. This is confirmed through power spectrum analysis. The power spectrum was computed (see e.g., Duari et al. 1992) as

$$P(k) = \frac{1}{N_{gal}} \times |F_N(k)|^2$$

with

$$F_N(k) = \sum_{n=1}^{N_{gal}} \exp(-ikz_n)$$

There is no statistically significant peak in the power spectrum in the individual fields or for the combined data. The galaxy distribution in the CFRS, for a largest dimension of $\sim 2500 \text{ h}^{-1} \text{ Mpc}$, is therefore much smoother than in the Broadhurst et al. (1990) surveys, and does not exhibit any preferred scale.

6. SPATIAL DISTRIBUTION OF GALAXIES

Localized peaks in the redshift distribution can be due either to dynamically bound clusters of galaxies with typical scales of the order

of one Mpc, or dense filaments with scales ≈ 10 Mpc. The CFRS survey has the ability to characterize the distribution of galaxies on transverse scales of $4h^{-1}$ Mpc at the median redshift of the survey. Since the redshift histograms of the five CFRS fields are highly suggestive that the lines of sight are crossing a large number of galaxy over-densities, this section aims to identify the most significant over-dense regions observed in our survey, and evaluate the type of spatial distribution of galaxies in these structures.

6.1. Density enhancements in $N(z)$ distributions

The galaxies are distributed in redshift with a “picket-fence” distribution as identified in shallower surveys. We show in Figure 6 that this type of distribution extends over the full dimension of the survey or $\sim 2500 h^{-1}$ Mpc, with prominent peaks obvious out to $z \sim 1$.

In order to identify significant density enhancements in the redshift distributions, we used the following approach. First, the local overdensity of galaxies was computed at redshift intervals of 0.001 summing over galaxies within $\pm 1500 \text{ km s}^{-1}$, corresponding to the typical spread in velocity of clusters of galaxies:

$$\text{Galaxy over-density} =$$

$$\sum_{-1500}^{1500} (N_{gal} - N_{gal,mean}) / \sum_{-1500}^{1500} N_{gal,mean}$$

where $N_{gal,mean}$ is the mean $N(z)$ distribution derived from our observed luminosity function (CFRS-VI), normalized to the number of galaxies with redshifts in each field. Then, we have defined a “signal/noise” for each peak as

$$S/N = \frac{N_{gal,3000} - N_{gal,mean}}{\sqrt{N_{gal,3000}}}$$

All peaks with an over-density larger than 2.5 and $S/N \geq 2.5$ have been retained and exam-

ined in detail. The seven peaks detected in this manner are listed in Table 2. Figure 6 presents the observed $N(z)$ distribution, the “smoothed” $N(z)$ predicted from the CFRS luminosity function, and flags the 7 significant peaks detected above. Figure 7 shows the projected distribution of the galaxies in these peaks for each field.

6.2. Projected Galaxy Density Enhancements

To check for possible correlations between the over-densities in redshift and over-densities in the projected spatial distribution of galaxies, the projected galaxy density has been computed in each of the fields in the following way. On each point of a grid of 500×500 pixels, each pixel being $1''.24$ square, the projected density has been computed for galaxies with $17.5 \leq I_{AB} \leq 22.5$ following the prescription by Dressler (1980)

$$D_{gal,proj} = 10/\pi \times r_{10}^2$$

The projected density maps are presented in Figure 8, after normalisation to the mean projected density in each field, and overlaid on the galaxies identified from the photometry (CFRS-I). No projected density enhancements with

$$D_{gal,proj}/D_{mean,proj} \geq 3.5$$

are seen in our magnitude range.

6.3. Individual Density Enhancements

6.3.1. Structure at $z=0.985$ in 1415+52

The most significant density enhancement in the redshift distribution is in the 1415+52 field, with an over-density of 12 and a S/N of 3.2 at a redshift $z=0.985$. This structure has been described in Le Fèvre et al. (1994), and is the strongest single density enhancement detected in all of the CFRS survey. One of the most remarkable properties for such a high over-density is the relatively uniform distribution of galaxies in this field as is evident in Figure 7. Further studies of this structure over a wider field are continuing.

6.3.2. A cluster at $z=0.78$ in 1000+25

The second largest over-density in the redshift distribution is found in the 1000+25 field with an over-density of 5 and a $S/N=3$. The galaxies identified in this structure are peaked around a number of close galaxies around galaxy CFRS10.1991 at $\alpha_{2000}=10^h00^m31.^s64$, $\delta_{2000}=+25^\circ17'11''$, as shown in Figure 8. The projected density of galaxies with magnitudes between that of the brightest galaxy and $I_{AB}=23.5$ shows a well-defined maximum with a peak density excess of 3.5, as shown in Figure 9. Within $0.5 h_{50}^{-1}$ Mpc, there are 37 galaxies brighter than $I_{AB}=22.6$ ($\sim m_3+2$), while only ~ 13 are expected based on the average CFRS counts. The $N_{0.5}$ parameter defined by Bahcall (1981) is therefore $N_{0.5}=24$, indicative of a moderately rich cluster. The observed velocity dispersion of 910 km s^{-1} is in good agreement with that predicted from the relationship between $N_{0.5}$ and the radial velocity dispersion (Bahcall, 1981), 960 km s^{-1} . Of the 12 galaxies with redshifts in this cluster (+1 in the supplementary catalog), 10 have $V-I$ colors redder than the color of a redshifted Sbc spectral energy distribution according to Coleman et al. (1980). This is also consistent with these galaxies being located in a region with a density comparable to that of rich clusters. An analysis of the spectrophotometric properties of galaxies in this cluster will be presented elsewhere.

This cluster would have been detected from the projected galaxy density for $17.5 \leq I_{AB} \leq 23.5$ only if the over-density threshold had been set lower than $3.5 \times \text{mean background}$. This demonstrates that searching for clusters at very high redshifts from the projected galaxy density alone is very challenging and, in general, only very rich clusters will be selected.

6.3.3. Large scale over-dense region in 0000-00

Examination of the redshift distribution for the 0000-00 field shows a broad peak at $z \sim 0.25$.

The distribution of galaxies in this peak is not identified by the above algorithm to be a significant over-density within a box $\pm 1500 \text{ km s}^{-1}$. However, the detection algorithm identifies an over-density of a factor 5.3 with $S/N=3.1$ when the exploration box is $\pm 3500 \text{ km s}^{-1}$. If this is confirmed by additional redshift measurements in this sparsely sampled field, this could be the indication that this pencil beam is crossing an over-density of galaxies with a typical scale of $70 h^{-1} \text{ Mpc}$.

6.3.4. Other over-dense peaks

As shown in Figure 6, the galaxies in the other peaks of the redshift distributions do not have any preferred spatial locations, and are more or less evenly distributed over the fields. For example, the third highest peak, in the 0300+00 field, has about 16 galaxies producing an over-density of 4.4 in the redshift distribution, but no apparent concentration in the spatial distribution. This probably indicates that, given the typical cross-section of our survey fields at the redshift of the peaks, $\sim 5 h^{-1} \text{ Mpc}$, our pencil beams are crossing sheets of galaxies similar to what is seen locally.

6.3.5. Galaxy distribution as a function of $V-I$ color in over-dense regions

Figure 10 shows the redshift distribution of galaxies redder or bluer than a present day Sbc galaxy in all our fields. Although the numbers are small, it is interesting to note that only the $z=0.78$ structure in the 1000+25 field has a predominantly red galaxy population (10 “red” vs. 2 “blue” galaxies), while the other structures show a roughly equivalent number of “red” and “blue” galaxies. This is consistent with the observed segregation of galaxy types in which early-type galaxies favor the regions of highest density while late-type galaxies are found preferentially in low density regions (Dressler, 1980). The peaks observed in our survey, apart from the $z=0.78$ peak in the 1000+25 field identified with the cluster

described above, sample regions which have lower densities than the rich cluster environments for which this effect is observed.

6.3.6. QSOs

Of the 6 QSOs identified in the CFRS sample, none is identified in a peak of projected galaxy density (see fig.2). Of the 3 QSOs at redshifts ≤ 1.2 , only the QSO 14.1303 is associated with a significant overdensity in the redshift distribution (Le Fèvre et al. 1994). A more detailed description of the QSO environments is given in Schade et al. (1995, CFRS-X).

7. SUMMARY

We have established the following results from the analysis of the spatial clustering of galaxies in the CFRS survey:

- (1) The slope of the projected correlation function $w(r_p)$ computed for the whole CFRS sample, i.e., at a mean redshift $z \approx 0.6$, is $\gamma = 1.64 \pm 0.05$, very similar to the local slope, and γ is therefore not strongly evolving with redshift.
- (2) There is clear evidence for evolution of the clustering amplitude with redshift. At $z \approx 0.6$, the amplitude of $\xi(r)$ is ~ 10 times lower than locally on scales $0.1 < r < 2h^{-1}\text{Mpc}$ ($q_0 = 0.5$).
- (3) The correlation length at $z = 0.53$ is $r_0 = 1.33 \pm 0.09h^{-1}\text{Mpc}$ for $q_0 = 0.5$. This is inconsistent with any known local population of galaxies if the clustering is fixed in comoving space; it is consistent with only the most weakly clustered local galaxies in the $\epsilon = 0$ weak growth case, and requires strong growth, $\epsilon \geq +1$ to match local B-selected samples of luminous galaxies. Our analyses of the evolving luminosity function (CFRS-VI) and of HST images of CFRS galaxies (CFRS IX) indicate that the population mix cannot have changed dramatically, hence growth of the clustering properties in the range $0 \leq \epsilon \leq 2$ must have occurred.
- (4) The computation of the correlation length with $q_0 = 0$ decreases the apparent value of the

ϵ evolutionary parameter by ~ 1 . At $z = 0.53$ the CFRS sample as a whole is best described by $r_0 = 1.57 \pm 0.09h^{-1}\text{Mpc}$ for $q_0 = 0$.

(5) There is no difference in the clustering of blue and red galaxies at redshifts above 0.5, while there seems to be a difference in clustering amplitude of 2.5 in the range $0.2 \leq z \leq 0.5$, similar to what is observed in local samples. This may be analogous to the Butcher-Oemler effect in clusters at similar redshifts.

(6) The distribution of galaxy pair separations in each of the fields, and in the full sample, does not exhibit any regular pattern similar to the $128 h^{-1}\text{Mpc}$ pattern found by Broadhurst et al. (1991).

(7) The two strongest peaks in the redshift distributions are identified with a large wall of galaxies at $z=0.985$ (Le Fèvre et al. 1994) and with a newly-identified moderately rich cluster of galaxies at $z=0.78$.

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Table 1: Results on $w(r_p)$

Redshift	N_{gal}	r_0	γ
0 – 1	565	1.5 ± 0.15	1.64 ± 0.05
0.2 – 0.5	186	1.83 ± 0.18	1.64 (fixed)
0.2 – 0.5	186	2.10 ± 0.15	1.58 ± 0.09
0.5 – 0.75	196	1.1 ± 0.15	1.64 (fixed)
0.5 – 0.75	196	1.36 ± 0.13	1.67 ± 0.16
0.75 – 1	130	1.05 ± 0.1	1.64 (fixed)
0.75 – 1	130	1.45 ± 0.1	1.69 ± 0.12
0.2 – 0.5 (red)	93	2.1 ± 0.2	1.64 (fixed)
0.2 – 0.5 (blue)	93	1.45 ± 0.25	1.64 (fixed)
0.2 – 0.5 (red–blue)		1.93 ± 0.39	1.64 (fixed)
0.2 – 0.5 (blue–red)		1.85 ± 0.41	1.64 (fixed)
0.5 – 0.8 (red)	96	1.21 ± 0.15	1.64 (fixed)
0.5 – 0.8 (blue)	139	1.3 ± 0.15	1.64 (fixed)
0.5 – 0.8 (red–blue)		0.95 ± 0.09	1.64 (fixed)
0.5 – 0.8 (blue–red)		1.10 ± 0.05	1.64 (fixed)

Table 2: Details of the highest peaks in the redshift distribution

Field	z_{peak}	N_{gal}^a	Over-density ^b	S/N	σ_v
0300+00	0.217	10 (12)	2.5	2.5	510
0300+00	0.612	16 (17)	4.4	3.4	1060
0300+00	0.707	13	3.4	2.9	900
1000+25	0.466	12 (14)	3.6	2.9	700
1000+25	0.778	12 (13)	5.0	3.0	910
1415+52	0.746	11 (12)	3.2	2.7	812
1415+52	0.986	12 (15)	12.0	3.2	873

NOTE.—^a Numbers in brackets include galaxies from the supplementary catalog, ^b Over-densities as computed for ± 1500 km s⁻¹

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Fig. 1.— The projected two-point correlation function $w(r_p)$ for the galaxies in the CFRS sample with $0 \leq z \leq 1$. Error bars are a direct $1-\sigma$ estimate from the field-to-field variations. The slope of the two point correlation function at the mean redshift of the survey $z \sim 0.56$ is $\gamma = 0.64 \pm 0.05$, and therefore γ is not strongly evolving compared to local galaxy samples. The amplitude of $w(r_p)$ is ~ 10 times lower at $z \sim 0.56$ than for local galaxy samples with $r_0 \sim 5h^{-1}\text{Mpc}$.

Fig. 2.— The projected two-point correlation function $w(r_p)$ for three redshift ranges 0.2–0.5, 0.5–0.75, 0.75–1. Measurement errors have been increased by 50% from the Poisson errors. There is clear evidence for an evolution of the correlation strength with redshift within our sample, as well as compared to local samples with $r_0 \sim 5h^{-1}\text{Mpc}$. In the three increasing redshift ranges, the CFRS galaxies have absolute luminosities $-17.0 \leq M(B_{AB}) \leq -20.0$, $-18.0 \leq M(B_{AB}) \leq -21.0$, $-19.0 \leq M(B_{AB}) \leq -21.0$ respectively (for $h = 1$). If the correlation length varies with galaxies luminosities (Loveday et al., 1995), our r_0 measurement for $0.2 \leq z \leq 0.5$ should be revised upward, possibly by up to 50%, for consistency.

Fig. 3.— The projected two-point correlation function $w(r_p)$ for the galaxies redder than an unevolved Sbc galaxy (filled squares) and bluer than Sbc (open squares). The two populations have indistinguishable properties in the high redshift bin, which indicates a strong evolution when compared to the strong difference in the clustering strength between early and late-type galaxies observed locally (Loveday et al., 1995).

Fig. 4.— The evolution of the correlation length with redshift. Filled squares represent values of r_0 computed for $q_0 = 0.5$, empty squares are for $q_0 = 0$, dotted vertical lines indicate the range of redshifts of each r_0 value. The short dashed line is for $\epsilon = 0$, the dotted line for $\epsilon = -1.3$, the long dashed line for $\epsilon = 0.7$, and the dot-dash line for $\epsilon = 2.1$ (see text). Values spanning the range of local correlation lengths reported for various samples in Loveday et al. (1995) have been indicated. The derivation of r_0 from $w(\theta)$ by Hudon and Lilly (1995) has been indicated by circles (filled: $q_0=0.5$, open: $q_0=0$). Coupled to the local measurements, and our knowledge of the properties of galaxies at high redshift, our data indicates that moderate to strong growth of the clustering is required ($0 \leq \epsilon \leq 2$).

Fig. 5.— Distribution of pair separations in comoving Mpc from all CFRS fields combined. There is no apparent periodic pattern.

Fig. 6.— Redshift distribution in the five CFRS fields, in redshift bins $\delta z = 0.007$. The mean galaxy density derived from the CFRS luminosity function (CFRS-VI) is indicated as a full line. The 7 peaks with a galaxy over-density ≥ 2.5 and a $S/N \geq 2.5$ (see text) are identified by diamonds atop the peaks.

Fig. 7.— Projected distribution of galaxies in each of the peaks identified by the detection algorithm. Apart from the galaxies in the cluster at $z=0.78$ in 1000+25, most galaxies in the peaks are distributed evenly within the measurement area (cf. fig.6).

Fig. 8.— Projected 2D galaxy over-density maps superimposed on the galaxies identified in photometry in the range $17.5 \leq I_{AB} \leq 22.5$ (ellipses). Blackened ellipses indicate the galaxies with a redshift identified from spectroscopy. The projected galaxy density has been computed with $D_{gal,proj} = 10/\pi \times r_{10}^2$, and then normalized to the mean projected galaxy density in each field. The lower right panel shows the distribution of normalized projected galaxy density in each field. The largest projected over-density is ~ 3.5 times the mean galaxy background.

Fig. 9.— Cluster of galaxies at $z=0.78$ in the 1000+25 field. The field shown is 120×120 arcsec² around $\alpha_{2000}=10^h00^m31.64^s$, $\delta_{2000}=+25^\circ17'11''$. The projected galaxy over-density is shown as contours starting at $1.5 \times$ the mean density, with spacings of 0.4, and it peaks at an over-density of 3.5 on the two brightest galaxies in the concentration. Thirteen galaxies have confirmed redshifts within several $km\,s^{-1}$ of the brightest cluster galaxy.

Fig. 10.— Redshift distribution of galaxies redder than a redshifted present day Sbc (shaded) compared to the redshift distribution of all galaxies (open). The mix of blue and red galaxies is relatively even in the high and low density regions, except for the $z=0.78$ peak in 1000+25, consistent with it being associated to a cluster of galaxies.



















